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Quarterly Technical Progress Report on Fundamental Hydrodynamics Research (ONR - Code 12)

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Prepared by Cognizant ARL Penn State Principal Investigators

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PREFACE

Under the sponsorship of The Office of Naval Research (Code 12) AHR Program, The Applied Research Laboratory of Penn State University performs basic research in hydrodynamics and hydrodynamic noise. The hydrodynamics research conducted under this program falls into two basic thrust areas:

- Turbomachinery

  To develop an improved understanding of the fluid mechanics and acoustics associated with low-speed turbomachines and marine propulsors. To employ this knowledge to the development of improved propulsor and turbomachine design methods.

- Drag Reduction

  To develop fundamental understanding of the mechanisms that cause drag on bodies and surfaces and to explore novel methods to reduce drag.

Under each thrust area, one or more projects are conducted under the direction of the principal investigator who initiated the given task. All tasks are designed to provide results that will improve the scientific understanding of various hydrodynamic phenomena associated with the operation of submerged bodies and surfaces.

This report documents the technical progress realized during the second quarter of FY 90 for the projects currently approved under this program.

Turbomachinery

SUBTASK T1

Title: Turbomachine Internal Flow Definition
(S. A. Abdallah, University of Cincinnati)

BACKGROUND

The internal flow field of a wake adapted turbomachine is dominated by three dimensional and unsteady effects. The three dimensionality of the flow field is demonstrated by the strong secondary flows which have been experimentally measured. The unsteadiness of the flow is due to the interaction of the downstream blade rows with the wakes shed from the upstream blade rows. The development of computational tools to accurately predict these types of flow fields is essential if successful development of high performance turbomachinery is to be achieved.

PROGRESS

Two ship hulls were computed for the 1990 SSPA Workshop on ship viscous flow. The first is the HSVA tanker for which data is available in the literature, and the second ship is a mystery case (modified HSVA) for which data will be available at the workshop.

Numerical solutions are obtained for the three-dimensional incompressible Reynold's averaged equations using a four-step Runge-Kutta method. The continuity equation is satisfied through the solution of a Poisson equation for the pressure. The Baldwin-Lomax turbulence model is used to calculate the eddy viscosity. A sample of the computed results for the HSVA tanker is shown in Figures (1) and (2). In Figure (1), the calculated axial velocity contours at $X/L = 0.956$ and $X/L = 1.005$ (the tanker starts at $X/L = 0$ and ends at $X/L = 1.03$) are compared with the experimental data of Larson and with Patel numerical results. The present results are in good agreement with the experimental data. Also, the computed secondary flow at $X/L = 0.976$ and $X/L = 1.003$ is shown in Figure (2). More details will be available at the workshop.

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1. Ship Stern and Wake Flows: Solution of the Fully-Elliptic Reynolds-Averaged Navier-Stokes Equation and Comparisons with Experiments by V. C. Patel, H. C. Chen and S. Ju. IIHR Report No. 323, (1989).

2. Sarda, O. P. "Turbulent Flow Past Ship Huffs - An Experimental and Computational Study," Ph.D. Thesis, Mech. Eng., Uni lower, (1980).

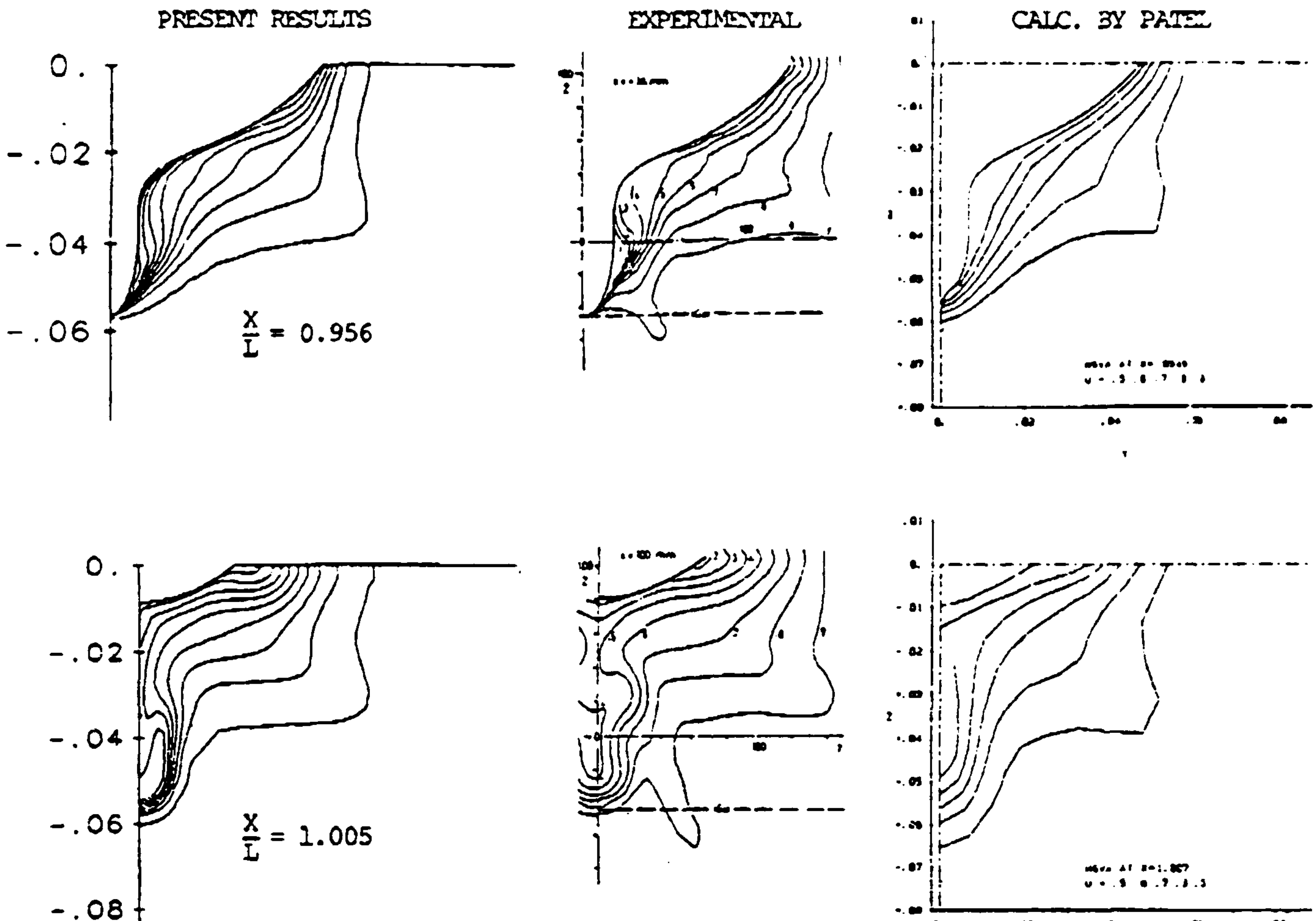

Fig. 1. Axial Velocity Contours

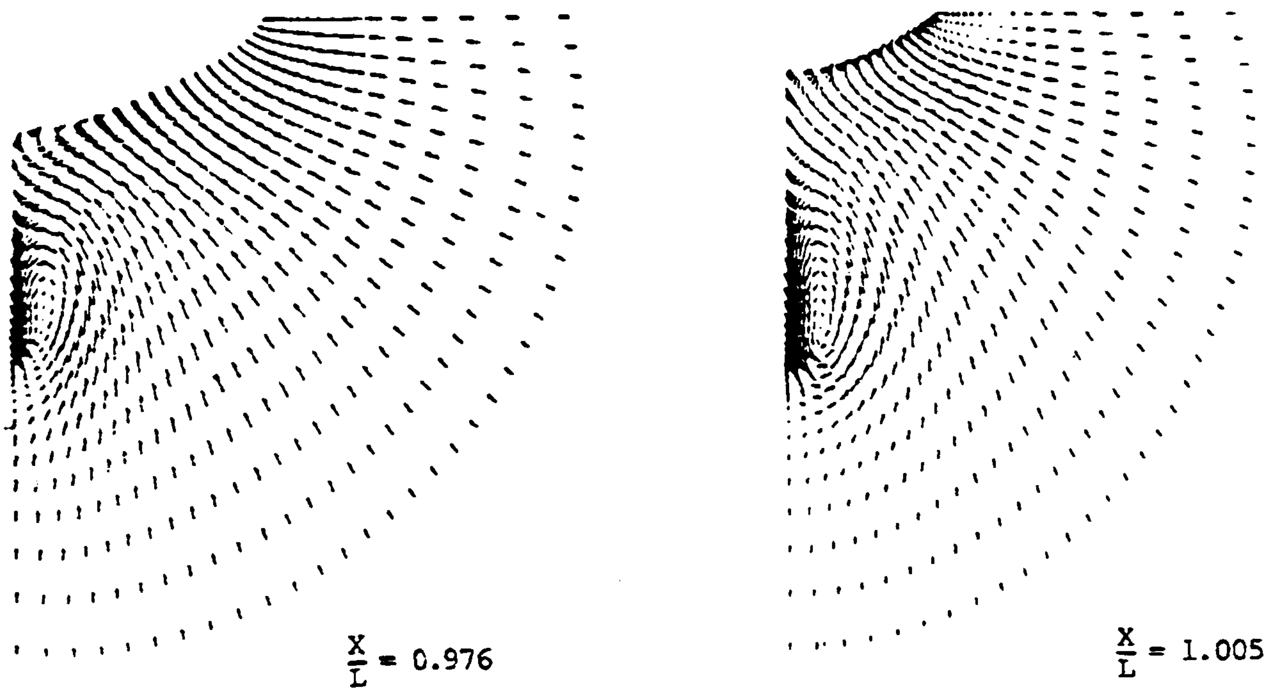

Fig. 2. Calculated cross flow

SUBTASK D1

Title: Turbulent Spot Generation by Freely Suspended Particles in a Flat Plate (H. L. Petrie and P. J. Morris)

Background

Laminar flow control (LFC) has been an attractive technology for many years but premature transition, induced by particles in the fluid, has prevented its successful hydrodynamic implementation. Although an extensive amount of experimental work and analysis has examined the transition induced by various types of roughness elements and intermittent disturbances such as sparks, basic questions regarding the mechanisms for transition induction by freely suspended particles still remain unanswered. The subject experimental and analytic study of particle induced transition is concerned with these issues and is entering the ninth month of activity.

Heated body LFC experiments have demonstrated clearly the degradation of LFC performance due to freestream particles. However, a detailed explanation of this phenomenon has not been developed. Experiments by Lauchle, et al [1], observed that nearly neutrally buoyant particles of sufficient size caused turbulent spots on an LFC heated body when seeded into the freestream. However, these particles failed to generate spots when injected through a dye port at the nose of the body. If these particles did not migrate away from the wall significantly while accelerating around the nose, then freestream seeded particles must act on the boundary layer with a different mechanism than the wall injected particles. This suggests that the dynamics of crossing streamlines and possibly wall impact may be crucial to spot formation. In support of this, Hall [2], observed that transition could be induced when a spherical particle supported by wire was pulled into the wall even though, once fixed to the wall, the particle was too small to induce a turbulent spot.

Progress

During this reporting period we have concentrated on making predictions of particle trajectories. The equations for the particle velocities were given in the last report. There were some minor errors in these equations so they are corrected below.

For flow along a horizontal flat plate the component equations are

$$\frac{dx_p}{dt} = U_p$$

$$\frac{dy_p}{dt} = V_p$$

$$\left(\frac{1}{2} + \frac{\rho_p}{\rho_f}\right)\frac{dU_p}{dt} = \frac{3}{2}\frac{DU}{Dt} + \frac{3C_D}{8a}(U - U_p)\Delta q$$

$$\left(\frac{1}{2} + \frac{\rho_p}{\rho_f}\right)\frac{dV_p}{dt} = -\left(\frac{\rho_p}{\rho_f} - 1\right)\frac{1}{Fr} + \frac{3}{2}\frac{DV}{Dt} + \frac{3C_D}{8a}(V - V_p)\Delta q + \frac{3C_L}{8a}(U - U_p)\Delta q$$

where

$$\Delta q = \left[(U - U_p)^2 + (V - V_p)^2\right]^{1/2}$$

In these equations we have neglected the lift force due to shear in the streamwise direction, as this will be of order $Re^{-1/2}$ compared to the corresponding term in the normal direction. We have also neglected the contributions of the Basset forces. If the later terms are included, a preferred formulation for the problem is given below. In this case the trajectory equation may be written,

$$\vec{A}_N = \vec{B}_N + C_N \vec{I}_{B_N} \quad at\ time\ t_N$$

where

$$\vec{A} = \frac{d\vec{V}_p}{dt} - \frac{D\vec{V}}{Dt}$$

$$\vec{B} = \frac{c_1 c_2}{Fr} j + \left(\frac{3c_1}{2} - 1\right)\frac{D\vec{V}}{Dt} + \frac{3C_D\, c_1}{8a}(\vec{V} - \vec{V}_p)\Delta q + \frac{3C_L\, c_1}{8a}[(\vec{V} - \vec{V}_p)\cdot \vec{i}\,]\Delta q \vec{i}$$

$$C = \frac{9}{2a\sqrt{\pi R}}$$

$$c_1 = \left(\frac{1}{2} + \frac{\rho_p}{\rho_f}\right)^{-1}$$

$$c_2 = \left(1 - \frac{\rho_p}{\rho_f}\right)$$

$$\vec{I}_{B_N} = -\sqrt{t_N}\,\Delta\phi_2 \vec{A}_N - \sqrt{t_N}\,\vec{K}$$

$$where\ \vec{K} = (\Delta\phi_2 + \Delta\phi_3)\vec{A}_{N-1} + (\Delta\phi_3 + \Delta\phi_4)\vec{A}_{N-2} + \ldots + \Delta\phi_N \vec{A}_1$$

$$where\ \phi^2 = 1 - \tau/t$$

Thus I_B can be eliminated and the particle acceleration at t_N can be found:

$$\left(\frac{d\vec{V}_p}{dt}\right)_N = \vec{A}_N + \left(\frac{D\vec{V}}{Dt}\right)_N$$

where

$$\vec{A}_N = \frac{\vec{B}_N - C\sqrt{t_N}\,\vec{K}}{1 + C\sqrt{t_N}\,\Delta\phi_2}$$

The drag coefficient is described by an empirical relationship to the Reynolds number,

$$C_D = \frac{24}{Re_b}(1 + T),$$

where

$$T = 0.197\ Re_b^{0.63} + 2.6\ x\ 10^{-4} Re_b^{1.38}, and,$$

$$Re_b = 2a\Delta qRe.$$

A similar expression has been developed for the lift coefficient due to shear. Because of a shortage of experimental data the dependence on Reynolds number has not been determined. The expression is based on data in the Reynolds number range of interest to the present investigation. The expression currently being used is,

$$\log_{10} C_L = 0.121 \log_{10}\left(\frac{2a}{u}\frac{du}{dy}\right) - 0.011.$$

Improvements on this expression for low values of shear are under investigation.

Calculations have been performed for a Reynolds number per meter of 2.5×10^5, ρ_p/ρ_f = 1.05 and 1.15, and a = 4×10^{-3} m and 6×10^{-3} m. This corresponds to a freestream velocity of 0.25 m/s. Figure 1 shows the trajectory of particles released from rest above the plate at x = -0.2 m, y = 0.25 m. Figure 2 shows the particle vertical position as a function of time. The Basset term has little effect for the cases considered. In addition, the lift force due to shear is negligible for two reasons. First, the particle travels in a nearly uniform flow for most of its trajectory. Second, the relative velocity of the particle when it enters the boundary layer is very small. This would not be the case if the particle were released closer to the edge of the boundary layer. The vertical velocity, the slope of the curves in Figure 2, is nearly constant for $y_p < 0.10$ m prior to entering the boundary layer. The less dense 4 mm particle has a vertical velocity of about 0.11 m/s or less than 45% of the freestream velocity near the wall. The denser 4 mm particle has a near wall vertical velocity that is approximately 78% of the freestream velocity. This behavior corresponds approximately to our expectations for nylon and polystyrene particles of this diameter. The 6 mm denser particle

is expected to have a vertical velocity near the freestream velocity as it falls into the boundary layer for the given conditions.

Plans

The assembly of the channel will soon be completed and flow field evaluation will commence. Initial experimental work will be concerned with the general quality of the channel flow. The test plate flow will also be evaluated and this will require some iteration on the plate setup. This requires both flow visualization and boundary layer surveys. Plans are to use an LDV system to do this.

The on-going activities include further refinement of the particle trajectory calculations and the prediction of wave packet development from fixed point sources. This latter study is the initial investigation leading to predictions for the generation of wave packets from moving sources.

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(1) Lauchle, G. C., Petrie, H. L., and Stinebring, D. R., "Effects of Particles on the Delayed Transition of a Heated Body," ARL Technical Memorandum, File No. 86-213.

(2) Hall, W. R., "Interaction of the Wake from Bluff Bodies with an Initially Laminar Boundary Layer," *AIAA Journal*, Vol. 5, No. 8, pp. 1386-1392.

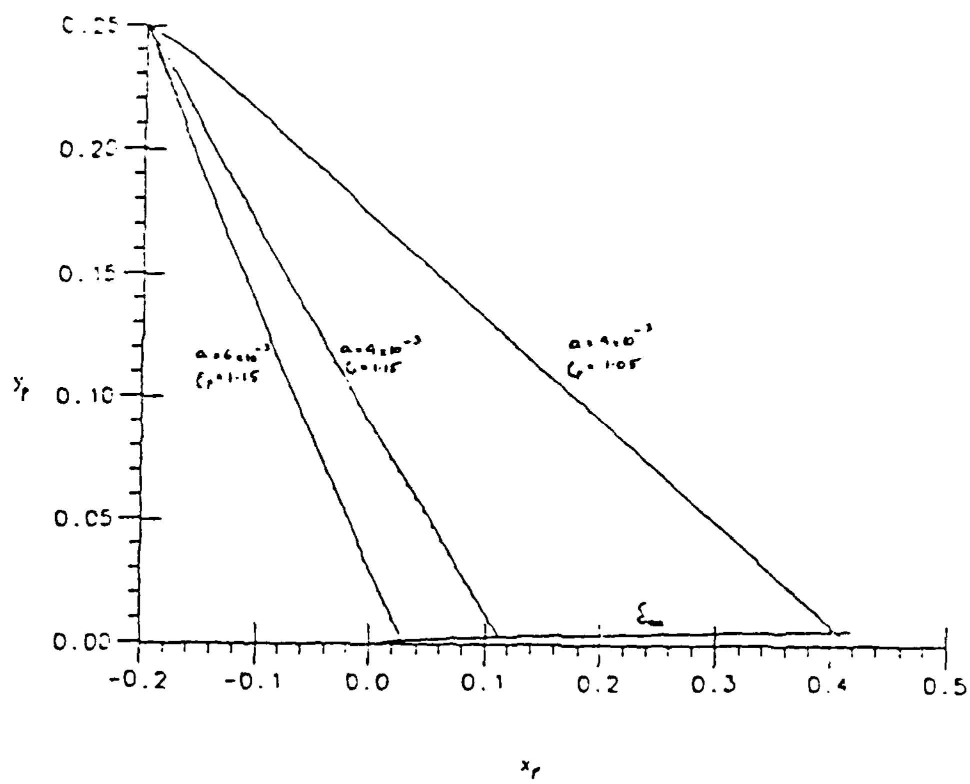

Figure 1. Particle trajectories for different specific gravities and particle radii —, including Basset term, ---, excluding Basset term.

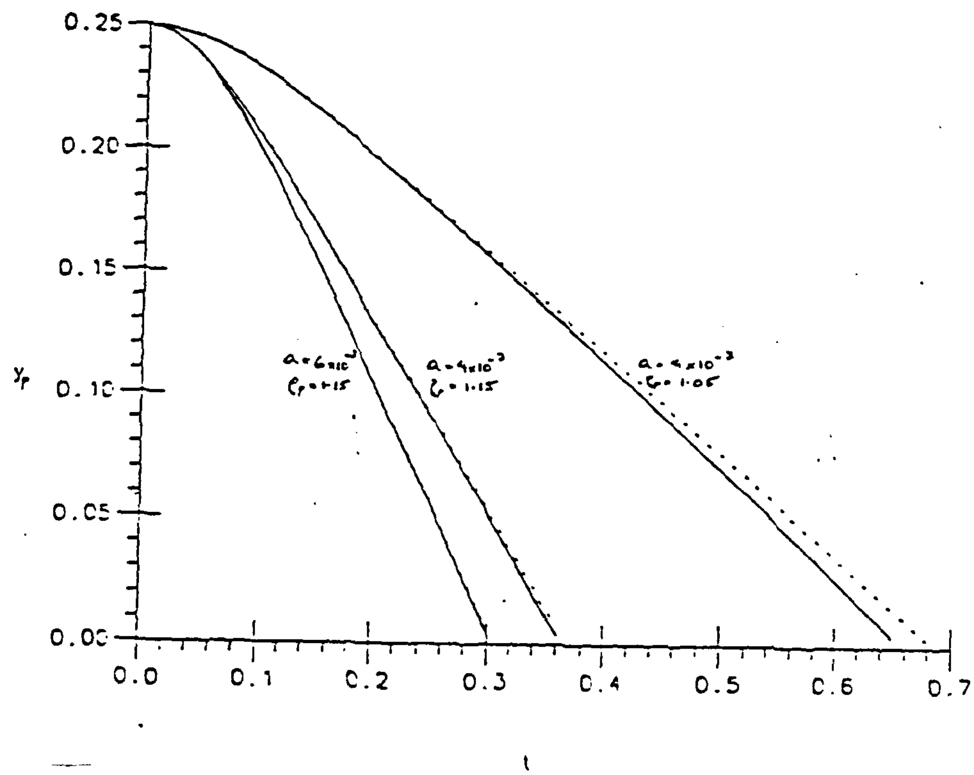

Figure 2. Variation of vertical position with nondimensionalized time. —, including Basset term, ---, excluding Basset term.

SUBTASK DR2

Title: Microbubble Injection in Axisymmetric Flows (S. Deutsch)

BACKGROUND:

It has been demonstrated that the injection of gas to form microbubbles in a liquid turbulent boundary layer on a flat plate at nominally zero pressure gradient can reduce skin friction drag by as much as 90% locally. The extension of these results to submerged axisymmetric bodies is the subject of this task.

PROGRESS:

A publication based on an extensive set of local skin friction measurements has been accepted (with revision) by the Physics of Fluids. Major results covered in the paper include the fact that the persistence of the phenomenon on an axisymmetric body is the same as that on a flat plate and that the poor performance of microbubble drag reduction at low speeds is a result of a buoyancy driven instability that removes bubbles from the boundary layer.

We are completing our study of the effect of pressure gradient. We have repeated our integrated skin friction measurements and LDV studies and have measured the pressure gradient on the body with and without bubble injection. Data analysis is complete and it appears that the earlier drag reduction data is repeatable and that injection of gas does not change the pressure gradient on the body. Relative levels of drag reduction would appear then to be correct, independent of the effect of pressure gradient on the balance results. Our earlier conclusions that an unfavorable pressure gradient led to higher levels of drag reduction and the prospect of early separation, while a favorable gradient led to much lower levels of drag reduction would appear to confirmed.

We are continuing simple computations of the flow field over the axisymmetric body for the zero, adverse and favorable pressure gradient cases. These computations, which employ the measured pressure gradients, will give us another test of the reliability of the absolute values of balance results in a pressure gradient.

Analysis of LDV data has shown that the axisymmetric body we are using is probably not seeing the same boundary layer growth as the body documented by Deutsch and Castano (1). The body currently in use has a longer injection filter section, and this larger region of roughness may have resulted in a thicker layer. To make the LDV results self-contained, we have measured the boundary layers for the zero pressure gradient case.

An abstract dealing with the results of our pressure gradient study has been submitted to the American Physical Society, Division of Fluid Mechanics, Annual Meeting. The presentation will be made in November.

PLANS:

The results sketched above will provide the basis for a M. S. Thesis in Aerospace Engineering for Mr. H. J. Clark as well as for an additional publication. We will spend the next few months preparing these documents.

1. Deutsch, S. and J. Castano, Physics of Fluids 29, 3590 (1986).

SUBTASK DR3

Title: Turbulent Boundary Layer Modification by Suction (H. L. Petrie)

Background

Small amounts of wall suction reduce boundary layer turbulence substantially. Data presented to the sponsor and discussed in past annual reports have shown that suction coefficients, C_q, as low as -0.0001 can reduce turbulent boundary layer (TBL) RMS and Reynolds stress levels noticeably. The suction coefficient is the ratio of the velocity induced by suction normal to the surface to the freestream velocity. This has the potential benefits of TBL flow quieting and may also be useful for reducing possible TBL sources of unsteady forces and noise affecting propulsors.

Speculative explanations for the effects of wall suction on TBLs have been given. Suction may counteract the ejection velocity of lifting streaks of low momentum fluid or suction may stabilize the sublayer to delay and prevent bursting at the wall. To date, most research involving suction with turbulent boundary layers (TBLs) has used discrete spanwise slots or continuously porous surfaces to apply suction. The emphasis of many of these past efforts has been on heat transfer and skin friction changes with suction. Much of this past work was limited to mean velocity profile measurements or turbulence measurement at relatively high suction rates. Recent flow visualization and hot-wire work by Antonia, et al (1988, 1989) has examined the effects of suction on the structure of the TBL in greater detail. The flow visualizations support that suction does stabilize wall streaks such that they oscillate less in the spanwise direction and persist longer prior to lifting.

Progress

The main piece of test hardware, a multi-plenum drag balance with the capability to accept porous surfaces with small flush mounted probes was modified at the end of the FY 88 funded period. The sensing members of the drag balance have undergone substantial improvements in sensitivity and zero drift since this work ended in FY 88 in support of another project.

The needed porous skins have been chemically etched in this last quarter and all that remains is to run the experiment. The drive control system for the 12-inch diameter water tunnel has undergone some modifications for better low speed operation. As a result of this work, the experiment has been delayed until evaluation of the tunnel and other projects are done with it.

Plans

The experiment will take place within the next quarter. The experiments will consist of drag balance measurements, LDV surveys, and surface pressure fluctuations measurements will be attempted.

Tailored and uniform suction at C_q from -0.0001 to -0.003 with freestream velocities of 5 and 15 fps will be studied. If time allows the case of a disturbed TBL flow will be examined at one velocity with one suction surface at three suction levels.

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2. Antonia, R. A. and Fulachier, L., "Topology of a Turbulent Boundary Layer with and without Wall Suction," JFM, V198, 1989, pp. 429-451.

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13. ABSTRACT *(Maximum 200 words)*
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14. SUBJECT TERMS
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